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Identification of $T = 0$ and $T = 1$ Bands in the $N = Z = 37$ Nucleus ^{74}Rb

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The γ decay of excited states in the $N = Z$ odd-odd nucleus ^{74}Rb has been observed for the first time. The reaction ^{40}Ca(^{40}Ca, αpn)^{74}Rb at 128 MeV beam energy was used. The ground state rotational band can be interpreted as being formed from the $T = 1$ isobaric analog states of ^{74}Kr with pairing correlations based on $T = 1$, $M_T = 0$ neutron-proton pairs. At higher rotational frequency, a $T = 0$ rotational band becomes energetically favored over the $T = 1$ ground state band, in agreement with the predictions of cranked shell model calculations which explicitly include $T = 0$ and $T = 1$ pairs.

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In recent years, it has become possible to populate and observe even-even $N = Z$ nuclei in the $A \approx 70-80$ mass region from ^{64}Ge up to ^{84}Mo [1,2]. Although such experiments are close to the current limits of sensitivity, the results have revealed dramatic and striking structural features, the majority of which can be attributed to the coincidence of neutron and proton Fermi surfaces. The nuclei around $A = 80$ are now known to be highly deformed and, as such, have been considered theoretically in terms of collective frameworks in which competing gaps in the Nilsson single-particle scheme at particle numbers 34 or 36 (oblate shape, $\beta_2 \approx -0.3$) and 38 (prolate shape, $\beta_2 \approx +0.4$) were predicted [3] and observed [1,4,5]. As yet, however, these approaches do not treat explicitly the isospin degree of freedom, which describes the neutron-proton (n-p) exchange symmetry associated with the charge independence of nuclear forces. In a recent study isospin impurities in ground states of $N = Z$ nuclei were investigated [6] and found to be small ($\approx$2% for $Z = 37$). Hence, the consequences of this symmetry in strongly correlated structures have yet to be fully explored.

The role of n-p pairing is of particular interest in this regard. Earlier studies, mostly in sd shell nuclei [7], suggest that n-p pairing should dominate in self-conjugate nuclei and that it may affect band-crossing phenomena [8,9]. For example, a ground state isospin $T = 1$ pairing band becomes energetically unfavored with respect to a $T = 0$ pairing band at spin $I = 5$ in the even-even $N = Z$ nucleus ^{24}Mg [10]. However, very little is known about medium mass $N = Z$ nuclei, especially the odd-odd isotopes where this pairing mode should be particularly revealed. The present study investigates the yrast states in the $N = Z = 37$ nucleus ^{74}Rb and provides the first experimental data to test some of these predictions.

High-spin states in ^{74}Rb were populated in two experiments using the reaction ^{40}Ca(^{40}Ca, αpn)^{74}Rb at 128 MeV beam energy. The Eurogam I array [11], consisting of 45 Compton-suppressed Ge detectors, was used to detect prompt γ radiation in coincidence with nuclear recoils identified with the recoil separator. Recoil-γ and twofold and higher-fold γ events were recorded. The target consisted of 250 μg/cm^2 ^{40}Ca enriched to 99.965%, evaporated onto a 10 μg/cm^2 carbon foil with a covering flash of gold. The second experiment was performed at the Nordball facility [12] using a 400 μg/cm^2 ^{40}Ca target, enriched to 99.99% and evaporated onto a 14 mg/cm^2 thick gold foil. The γ radiation was measured in 19 Compton-suppressed Ge detectors at 37°, 79°, 101°, and 143° relative to the beam axis. Efficient channel selection was possible by detecting evaporated charged particles in a 4π silicon ball consisting of 20 segments. Seven liquid scintillator detectors and 30 BaF_2 scintillators served as neutron and γ multiplicity filters.

In the first experiment it was possible to identify the recoiling nuclei by A and Z but the statistics were not good enough to assign γ rays unambiguously to the weak αpn exit channel, ^{74}Rb. Accordingly, the γ rays were identified from inspection of the various particle-γ coincidences recorded in the Nordball experiment. All of the spectra with the gating conditions of 0–6 protons, 0–3 α particles, and 0–3 neutrons were sorted. By successively subtracting spectra with higher particle detection folds from the lower-fold spectra, "pure" spectra were produced, each containing γ radiation from only one of the following isotopes: ^{71,73,75}Br, ^{72,74,75,76}Kr, ^{74,75,76,77}Rb, and ^{77,78}Sr. Figure 1(a) illustrates the "pure" spectrum in coincidence with αpn detection leading to ^{74}Rb. Apart from previously unknown lines at 218, 303, 478, 483, 520, 528, and 575 keV assigned to ^{74}Rb, the strongest transitions from ^{81}Rb and ^{82}Rb are present. They originate from $\alpha p2n$ and αpn channels of the $<0.01\%$ component of ^{48}Ca in the target. The relative cross section of ^{74}Rb was estimated to be 0.11(4)% from normalized yields of the ground state transitions in the known residual nuclei. Calculations [13] predict a total fusion cross section of 380 mb, leading to a 0.4(2) mb cross section for the formation of ^{74}Rb. The reaction ^{48}Ca(^{40}Ca, $\alpha p2n$)^{81}Rb is predicted to be 120 mb, making ^{81}Rb the most important contaminant in the "pure" αpn spectrum. Figure 1(b) presents the sum of spectra gated with the 218, 303, 483, 520, and 528 keV transitions in the $n\gamma\gamma$ matrix. The origin of the new transitions from ^{16}O and ^{12}C target contaminants can be ruled out from the spectrum in Fig. 1(c). It is the sum of spectra in coincidence with the 218 and 303 keV transitions in the ^{74}Rb $\gamma\gamma\gamma$ matrix from the Eurogam data, which contains $\gamma\gamma\gamma$ events with one γ ray being either the 218, 265, 303, 478, 483, 520, 528, or 575 keV transition. The nuclei were observed in flight and the γ-ray energies had to be Doppler corrected and the resulting peaks are Doppler broadened. The recoil velocity is significantly lower for reactions with ^{40}Ca compared to reactions involving ^{16}O or ^{12}C nuclei and would lead to broad multipeaks for the latter in Fig. 1(c). The statistics are too poor to observe angular correlations in either of the experiments. However, the Nordball data allowed us to generate ^{74}Rb spectra at $37° + 143°$ and $79° + 101°$. The ratios of the yields of the transitions in the two spectra were used to determine their multipolarities.

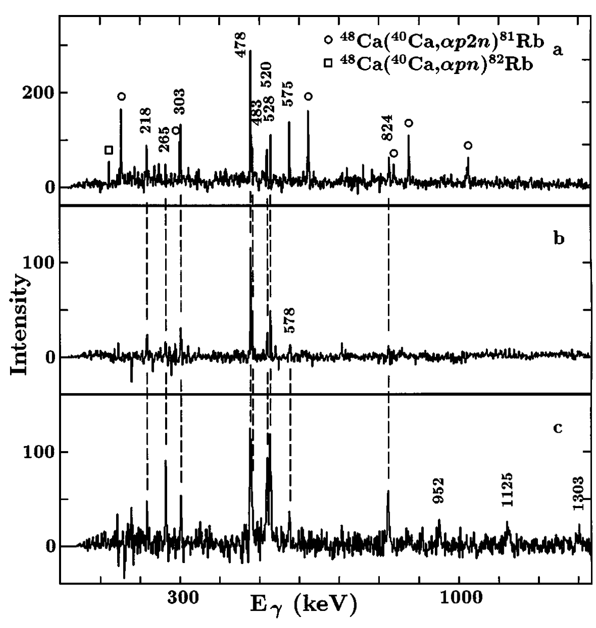

FIG. 1. Spectra containing transitions from ^{74}Rb in coincidence with (a) one α particle, one proton, and one neutron, (b) the 218, 303, 483, 520, and 528 keV transitions and a neutron (Nordball), and (c) the 218 and 303 keV transitions in the ^{74}Rb triples matrix (Eurogam). The energy labels are in keV and indicate γ rays assigned to ^{74}Rb. Contaminations arising from ^{48}Ca in the target are marked with ○ and □.

The level scheme deduced for ^{74}Rb is presented in Fig. 2. Since, in general, low lying isomeric states are expected in odd-odd nuclei, we also looked for delayed particle-$\gamma\gamma$ coincidences. However, no isomeric γ rays were found above 50 keV in ^{74}Rb. In addition, a second β-decaying state with $T = 0$ was not observed, though searched for by D'Auria *et al.* [14]. They reported the Fermi superallowed $(0^+ \rightarrow 0^+; T = 1)$ β^+ decay of ^{74}Rb. Therefore, the most intense 478 keV transition, which is consistent with $E2$ character, is assumed to feed the 0^+ ground state. The 575 keV transition was found to be in coincidence only with the 478 keV transition. The extension of the left-hand side of the level scheme was not feasible, due to strong contaminations. On the right-hand side the other ^{74}Rb lines were grouped on top of the 478 keV state. Up to the 1489 keV level the excitation is rather irregular. Thereafter, a sequence of states develops which follows an $I(I + 1)$ pattern.

The excited levels in ^{74}Rb are completely different from those of neighboring odd-odd nuclei with $N \neq Z$. These nuclei develop several strongly coupled $\Delta I = 1$ rotational bands at very low excitation energies [15]. It is interesting to note that the presumed $4^+ \rightarrow 2^+ \rightarrow 0^+$ ground state band (575–478 keV) is close in energy to that in the isobar ^{74}Kr (558–456 keV). Hence, we propose that these nearly "identical" bands result from the fact that they are $T = 1$ isobaric analog states. Such an interpretation carries with

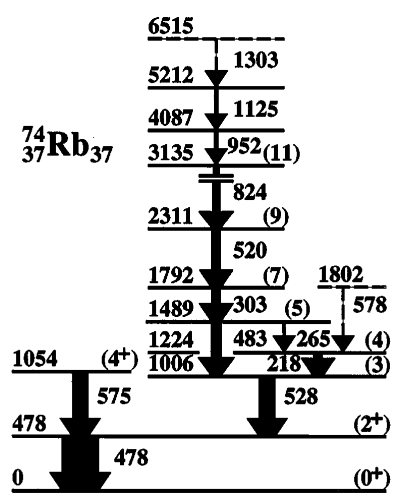

FIG. 2. Level scheme of ^{74}Rb deduced from the present work. The widths of the arrows are proportional to the relative γ-ray intensities. The intensities of the 303 and 520 keV as well as those of the 952 and 1125 keV transitions are equal within their errors. Note the change in energy scale at 3 MeV.

it certain implications concerning the pairing correlations in the odd-odd nucleus and, in particular, is consistent with the recently suggested [16] reappearance of a pairing gap in $N = Z$ odd-odd nuclei in this region.

The pairing correlations encountered most frequently are $T = 1$, $M_T = \pm 1$, i.e., neutron or proton pairs in time-reversed orbits. In an odd-odd nucleus with larger neutron excess there should be no pairing gap and the rotational bands are characterized by $K = |\Omega_n \pm \Omega_p|$. Ω_n and Ω_p represent the projection of the single-particle angular momenta of the "unpaired" neutron and proton on the deformation axis. The bands are spaced simply according to the summed single-quasiparticle energies of the possible combinations of orbits with Ω_n, Ω_p. The relevant energies in ^{74}Rb in the standard Nilsson model are shown in Table I for a prolate deformation $\beta_2 = 0.3$. Note that the effect of Gallagher-Mozkowski splitting [17] and the Newby shift [18] resulting from the residual n-p interaction has been ignored, since both typically give rise to shifts of $\leq$200 keV. The intention here is simply to indicate the high density of states likely to arise in the absence of n-p pairing. In fact, the Nilsson orbits of Table I would give rise to a total of 72 rotational band heads below 2 MeV in ^{74}Rb, and the coupling rules [17] for an odd neutron and proton occupying Nilsson orbits with the same $\Omega = 3/2$ imply that the ground state band should have $K^\pi = 3^+$. Even allowing for the separation induced by the isospin quantum number, the single-particle space still gives rise to a total of 36 $T = 1$ bands.

When neutrons and protons are filling identical orbits, the possibility of n-p pairing correlations needs to be considered [7]. The last neutron and proton simply add one additional pair to the correlated ground state rather than constituting a two-quasiparticle state. The correlations can involve $T = 1$ pairs in time-reversed spatial orbitals, while $T = 0$ allows for pairing between identical orbits as well. The $T = 0$ interaction is normally assumed to be the most attractive, and this is borne out by the fact that the $N = Z$ odd-odd nuclei with $A < 40$ (except ^{34}Cl) have a $T = 0$ ground state. It also agrees with the results of generalized Hartree-Fock-Bogoliubov calculations incorporating both $T = 0$ and $T = 1$ n-p pairing [7,19] where $T = 0$ pairing was indeed found to dominate in $N = Z$ nuclei and to *compete* with $T = 1$, $M_T = \pm 1$ pairing for $N = Z + 2$. For larger N, inclusion of the $T = 0$ mode was unnecessary because the advantage of the larger number

TABLE I. Single-particle orbits near the Fermi surface in ^{74}Rb.

Nilsson orbit	$E_{\rm qp}^{\rm proton}$ (MeV)	$E_{\rm qp}^{\rm neutron}$ (MeV)
$3/2^+[431]$	0.000	0.000
$3/2^-[312]$	0.349	0.356
$3/2^-[301]$	0.359	0.452
$5/2^+[422]$	0.423	0.346
$1/2^+[440]$	0.472	0.495
$1/2^-[310]$	0.965	0.887

of like nucleon pairs rapidly outweighs that of the more attractive $T = 0$ interaction. Interestingly, $T = 1$ n-p pairing was never found to be important in these studies.

In the 28–50 shell, however, the ground states of the heavier mass odd-odd $N = Z$ nuclei seem to favor $T = 1$, in agreement with earlier predictions [20] based on extrapolated masses and also with the behavior of the empirically determined n-p interaction strength in both odd-odd and even-even nuclei which exhibits large attractive "spikes" at $N = Z$ which rapidly decrease with increasing mass. This behavior has recently been shown [21] to arise from, and to reflect, the gradual erosion of the Wigner spin-isospin symmetry as a result of the increasing importance of both the spin-orbit term in the nuclear potential and of the Coulomb interaction. In ^{74}Rb the same number of either $T = 1$ or $T = 0$ n-p pairs can be made and the favored mode will depend on the strength of the interaction. The current results thus suggest that, by the time $N = Z = 37$ has been reached (and probably considerably earlier), the trends cited above have resulted in the $T = 1$ pairs becoming the most attractive.

We turn now to the effect of increasing rotational frequency. In the standard cranked shell model (CSM) approach [22], neutrons and protons align their spins with the axis of rotation independently of each other. The residual n-p interaction is disregarded. This approach is known to give a reasonable description of the high-spin behavior of deformed nuclei with $N > Z$. However, for particle stable nuclei with $N \approx Z$, the residual n-p interaction should be explicitly considered. The model Hamiltonian consisting of a cranked deformed one-body term and a scalar two-body interaction was described in Refs. [9,23]. In this model, the interaction of the nucleons in the intruder valence subshell with the core nucleons is approximately described by the quadrupole field generated by them and the eigenstates have good parity, signature, and, most important, isospin. The deformation energy κ is expressed in units of G, where G is the strength of the δ interaction which is assumed here to be the two-body residual interaction. κ is related to the usual deformation parameter β_2 via $\kappa = 51.5A^{-1/3}\beta_2$ MeV [24]. Calculated band-crossing frequencies in neighbored even-even nuclei [25] and shell model calculations in $A \approx 90$ isotopes [26] suggest $G = 1.0$–1.5 MeV.

The Routhians for the one-proton plus one-neutron system coupled to an axially symmetric deformed prolate core with $\kappa = 2.4G$, i.e., $\beta_2 = 0.2$–0.3, are presented in Fig. 3. The ground state in Fig. 3 at $\hbar\omega = 0$ has even-spin values and a predominant $(J = M_x = 0; T = 1)$ component with amplitude 0.83 and finite contributions from $(J = 2, M_x = 2, 0, -2; T = 1)$ configurations. J denotes the intrinsic particle angular momentum, and this has to be coupled to the rotor angular momentum to obtain the total angular momentum in the laboratory frame; M_x is the projection of J on the rotational axis. As is evident from Fig. 3 the aligning $T = 0$

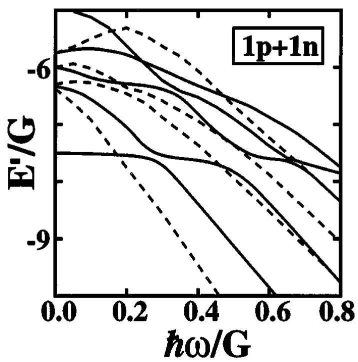

FIG. 3. The Routhians for the one-proton plus one-neutron system coupled to an axially symmetric mean field with prolate deformation. The full lines correspond to even-spin states and the dashed lines belong to odd-spin states. The first crossing along the yrast line is observed at $\hbar\omega = 0.2G$ and is due to the crossing of a $T = 0$ aligning configuration with the $T = 1$ ground state band.

configuration becomes immediately favored in energy at $\hbar\omega \approx 0.2G = 0.2$–$0.3$ MeV, consistent with the value of the experimental Routhians of $\hbar\omega \approx 0.28$ MeV. This "crossing" is diabatic since the ground state band and the aligning configuration have different isospin. The aligning configuration at $\hbar\omega = 0.2G$ is mainly comprised of the configurations $(J = 9, M_x = 9, 7, 5; T = 0)$ with amplitudes 0.85, -0.36, and 0.18, respectively.

The interesting implication of the above analysis is that for odd-odd nuclei with $N = Z$, the first alignment along the yrast line is not due to the conventional breaking of two-proton or two-neutron pairs but is due to the spin alignment of an n-p pair. As observed in ^{74}Rb, the aligned configuration with odd-spin states ($T = 0$) is quickly lowered in energy relative to the ground state band with even-spin values ($T = 1$). This "crossing" of a $T = 1$ pairing ground band by a $T = 0$ pairing band at a critical spin was also predicted in earlier studies of even-even $N = Z$ sd shell nuclei [10,27,28]: The Coriolis force destroys pairs composed of two nucleons in time-reversed orbits while it reinforces the n-p pairs in identical spatial orbits. In the latter case the Coriolis force has exactly the same effect on the neutron and the proton, so that they can both be aligned towards the axis of rotation without breaking the pair [8].

The crossing shown in Fig. 3 is not very sensitive to the magnitude of the deformation but depends on the two-body interaction used. With a more realistic interaction, such as the modified δ interaction, the energy spacing becomes larger with the consequence that the crossing seen in Fig. 3 will occur somewhat later. We also carried out the CSM analysis with oblate deformation since the core nucleus ^{72}Kr may have coexisting prolate and oblate shapes in the low spin regime [4]. The crossing between the two isospin bands with $\kappa = -2.4G$ is delayed to $\hbar\omega = 1.1G$.

To conclude, we observed for the first time excited states in the heaviest $N = Z$ odd-odd nucleus ^{74}Rb so far identified. The ground state band is proposed to consist of the $T = 1$ isobaric analog states seen in ^{74}Kr and to exhibit n-p pairing. The $T = 0$ odd-spin states become yrast at about 1.5 MeV excitation energy. Cranked shell model calculations using an axially symmetric deformed prolate core and explicitly including the residual neutron-proton interactions account for that phenomenon.

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